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STELLAR RADIOMETRY.

By Keivin Burns.

Dr. W. W. Coblentz[1] has recently put a new instrument at the disposal of astronomers. Besides a description of this instrument, the article referred to above contains a list of over a hundred stars whose total energy was measured by Dr. Coblentz. It is the purpose of the present note to compare the total energy with the visual and photographic magnitudes of these stars; to compare the spectral energy distribution with that of a black body, and to make some suggestions as to further work with the radiometer. Dr. Coblentz wishes me to emphasize at the outset the fact that his work was that of a pioneer, designed rather to show that positive results could be obtained than to make the most accurate measurement on a group of stars. The installation was merely temporary and few stars were observed more than once each.

In making the following tables, I have omitted *α Virginis* on account of its being observed near the horizon; *α Arietis* was omitted on account of suspected faulty classification; and *α Herculis* seems to be in a class by itself.

The results obtained by means of the radiometer are expressed in terms of the galvanometer deflection, the numbers being proportional to the total energy less atmospheric absorption. The deflections were translated into magnitudes to facilitate comparison with the visual and photographic data at hand. The radiometric minus the visual magnitude, and the radiometric minus the photographic magnitude was found for each star, and the mean taken for each spectral class. (I shall refer to these data hereafter as rad.-vis. and rad.-phot.) The data found in Harvard Revised Photometry[2] was used for the visual and photographic magnitudes. It is to be noted that the photographic magnitude as here given is based on the intensity of the spectrum at the G line, λ 4320A.

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[1] *Lick Observatory Bulletin,* **8**, 104, and *Bulletin Bur. Stand.,* **11**, 613.
[2] *Harvard Annals,* 50.

TABLE I.

Comparison of Radiometric with Visual and Photographic Magnitudes.

Class.	Limits.	Rad.-Vis.	No.	p. e.	Rad.-Phot.	No.	p. e.
B1	B-B2	—0.30	8	.08	—0.89	6	.13
B4	B3-B5	—0.40	4	.18	—0.6	2	..
A	B8-A2	—0.28	22	.04	—0.75	10	.10
A5	A3-A5	—0.21	5	.07	—0.83	4	.06
F	F	—0.8	1	..	—1.4	1	..
F5	F5	—0.5	2	..	—1.2	1	..
G	F8-G	—0.96	12	.09	—2.02	10	.10
G5	G5	—1.2	2	..	—2.1	1	..
K	K-K2	—1.12	21	.06	—2.46	21	.09
K5	K5	—1.69	5	.16	—3.69	5	.25
Ma	Ma	—2.20	10	.06	—3.70	8	.14
Mb	Mb	—2.7	2	..	—4.7	1	..
N	N	—3.2	1	..	......	..	..
α Herc	Mb	—4.2	..	..	—5.8	..	..

A glance at the column headed rad.-vis. shows that there is a tendency toward a maximum at class A5, and that the so-called earlier classes do not differ so very much in this datum. In fact, the rad.-vis. is the same, within the limits of error, for the classes B1 to A5. Only three stars of a class between A5 and F8 were observed. The total intensity of class G and K stars is twice that of class B and A stars of the same visual magnitude, and this ratio increases with advancing age until class N stars are fifteen times as rich in energy as class A stars of the same visual brightness, and *α Herculis* is relatively weaker still in visible rays. It is interesting to note that within the errors of observation stars of class K do not differ from those of class G in the ratio of visible to total energy. This is in agreement with the classification of Sir NORMAN LOCKYER, in which stars of classes G and K are put together. It is evident from the values of rad.-phot. that the spectra of these classes have a different energy distribution, and this may also be easily seen from a study of the photographic spectra. From K to K5, K5 to Ma, Ma to Mb and Mb to N there is a progression of striking regularity in the value of rad.-vis. If our eyes had the same sensitivity curve as the radiometer, *Antares* would be the brightest star in the summer sky, and *Betelgeux* the brightest one observed by Dr. COBLENTZ; the latter is no doubt nearly the equal of

Sirius in total intensity. The comparison of the intensity of the stellar spectra at λ 4320A with the total energy (Table I, column 6) shows that the ratio of these quantities is the same within the limits of error for stars of classes B to A5. This result was not expected as the work of KING, PARKHURST and others has conclusively shown that class B stars are brighter photographically than stars of class A of the same visual magnitude. However, in determining the photographic magnitudes these investigators used the integrated photographic intensity, and the data of Table I refers to the intensity at a given point in the spectrum. From A5 to Mb the photographic intensity falls off irregularly and, as is well known, very rapidly. Thus *β Pegasi* and *α Herculis* (class Mb) are respectively 35 and 100 times as rich in total energy as a star of class B or A of the some photographic magnitude.

When the stars are grouped according to class, it is seen that the values of rad.- vis. agree to within a few tenths of a magnitude in most cases. This is true even of the observations of the very faint stars, where the galvanometer swing is less than a millimeter, showing that the faint stars can be observed with considerable accuracy. Of the eleven stars which were observed more than once, only two depart more than two-tenths of a magnitude from the mean rad.-vis. for their class. It is likely that, whenever the departure is as much as three or four-tenths of a magnitude, the star in question will be found to have an energy curve differing from the mean for its class *β Ophiuchi* was observed twice and it appears to be half a magnitude weaker in total energy than other class K stars of the same visual magnitude. *α Herculis,* class Mb, was observed several times and it was found to be abnormally strong radiometrically, the value of rad.-vis. being greater for this star than for 19-*Piscium,* class N.

Double Stars.—Four faint companions were measured, all of which have been called "blue." The color is not borne out by the radiometric observations, as the rad.-vis. is in every case the same as that of the primary within the limits of observation. Of thirty-nine isolated stars of class B to A5, only one had rad.-vis. as large negatively as the smallest value for a companion star given in this table.

TABLE II.

Rad.-Vis. for Double Stars.

	Star A.		Star B.			
Name.	Class.	Rad.-Vis.	Class.	Rad.-Vis.	Separation.	Notes.
γ *Andromedæ*	Kp	—1.4	A	—1.4	10″	B is double Common P.M.
β *Scorpii*	B1	—0.4	"Blue"	—1.0±	14″	A is double Common P.M.
α *Herculis*	Mb	—4.2±	"Blue"	—4.5	4″.6	Common P.M.
β *Cygni*	Kp	—1.2	B9	—1.3	34″	Common P.M.

In the case of α *Herculis,* irradiation from the primary may have caused the secondary to be measured too strong; this is not likely to have been the case with the other stars,—it could not have happened in the case of β *Cygni.* These early class and "blue" companions appear to be relatively strong in total energy. It will be a very useful piece of work to investigate double stars radiometrically, even tho close pairs cannot be observed.

Parallax and Absolute Magnitude.—The absolute total intensity was computed for those stars for which the parallax has been observed. As there were only twenty of these, the statistics are not of much value. Among these stars there is no tendency for one class to be more intense than another. The rad.-vis. is not a function of absolute intensity. When rad.-vis. is plotted against parallax it appears that the more distant stars are somewhat weaker visually than are the closer stars, but more data will be necessary in order to be certain of this. The photographic data for the parallax stars is lacking.

Comparison of Transmission thru Water with Rad.-Vis.—The percentage of transmission thru a water cell is given by Dr. COBLENTZ for a few stars of the classes B8 to Mb. When these percentages are plotted against rad.-vis., the points fall close to a smooth curve if we use the rad.-vis. for the individual stars. This curve has a sharp bend at 69 per cent, class A5. If, instead of using the rad.-vis. for the individual stars, we use the mean for the class, the points do not fit a curve. This strengthens the view, expressed above, that the energy distribution in individual stars may depart quite widely from the mean distribution for a class.

PLANCK'S *Distribution Law and Temperature.*—PLANCK'S law of the distribution of energy in the spectrum of a luminour body $E_\lambda = C_1 \frac{1}{\lambda^5 (e^{\frac{c_2}{\lambda T}} - 1)}$, has been used by several investigators, notably by WILSING and SCHEINER, to estimate the temperatures of the stars. It is evident that most stars do not follow this, nor any other simple law of distribution, exactly. For the stars of early and late types have strong emission lines, or strong absorption bands or both. Furthermore, there is no certainty that the radiation from any substance will follow PLANCK'S law at temperatures far above that at which the substance becomes a gas. However, some of the stars have energy curves which so far as we know follow this law at least roughly, and it will be of interest to see for what classes of stars the law is entirely inapplicable. Accordingly, the distribution curves were plotted for temperatures ranging from 2000° to 9000° Abs., and these curves were corrected for atmospheric absorption. The visibility of each corrected curve has been found, the intensity at the G line, and the percentage of transmission thru 1^{cm}. of water in a quartz cell such as was used by Dr. COBLENTZ. Table III gives the atmospheric transmission which was used; the values were derived from the results contained in *Publications of the Smithsonian Astrophysical Observatory,* Vol. III. I aimed to find the transmission for Mt. Hamilton, where Dr. COBLENTZ made his measurements. For the work done with the water cell furnishes the most important data which we have relating to spectral energy distribution of the stars. Furthermore, no permissible values of the atmospheric transmission in different parts of the spectrum would have any great effect on the ratio of total energy to visibility, and the effect on the relation between total energy and intensity at 4320A would not be very great. Table III also contains the values which were used for the sensitivity of the eye to various wavelengths, and the transmission thru a water cell 1^{cm}. thick.

TABLE III.

Percentage of Transmission and Visibility at Various Wave-Lengths.

Medium \ λ in 100A	30	35	40	45	50	55	60	65	70	80	90	100	110	120	130	140	200	300
Atmosphere	0	50	63	72	79	81	84	86	89	90	92	94	94	94	94	94	93	93
Water	80	85	85	85	85	85	85	85	80	75	70	50	30	15	10	0	0	0
Visibility	0	0	4	8	34	100	63	11	1	0	..	..	..	..	..	..	..	..

Denoting by 100 the intensity of the energy which would penetrate the atmosphere, the value of the energy outside the atmosphere is given in Table IV for a black body ranging in temperatures from 2000° to 9000°. The line opposite "water" gives the percentage of the energy penetrating the atmosphere which would be transmitted by the water cell. Opposite "visibility" are found numbers which give the ratio of the visibility to the total energy. To get these numbers I multiplied the ordinates in the black body curve (as transmitted thru the atmosphere) by the percentages opposite "visibility" in Table III, and then took the ratio of the area under the resulting curve to that under the curve before the ordinates were reduced. Opposite "λ 432" are found numbers expressing the intensity at the G line on an arbitrary scale.

TABLE IV.

Data from Black Body Curves.

Temperature	2000°	3000°	4000°	5000°	6000°	7000°	8000°	9000°
Outside atmosphere	110	110	111	117	125	140	160	185
Water	8	26	40	51	58	67	72	74
Visibility	0	2.7	7.7	12	15	17	19	20
λ 432	0	1.0	4.8	12	17	20	22	24

Considering Table IV we find that if we had stars of all temperatures whose spectral energy curves obeyed PLANCK's law we could readily measure the temperatures by means of the transmission thru water until we reached the temperature 8000°. After this temperature the estimates would be indeterminate, as the water transmission varies but little and approaches 75 per cent. Again, if we knew the temperature of one of the stars, we could compute the temperatures from the visibilities, but here also the values would be indeterminate for the higher temperatures. What is true of the visibilities applies also to the photographic intensities. The temperatures computed in the three ways would agree, of course. The indeterminateness at high temperatures is brought about by the absorption in the atmosphere. Comparing columns 3 and 6 of Table I with lines 4 and 5 of Table IV we see that we are dealing with similar curves. This leads us to suppose that we may be able to relate the rad.-vis. and rad.-phot. with the temperatures of a black body. We shall see that the data collected by Dr. Coblentz shows that this cannot be done, as the required water transmission is greater than that which was observed in the case of the early type stars.

For each of the stars whose energy transmission thru water has been measured, Table V gives this transmission in per cent., the rad.-vis., and rad.-phot. The last datum is for the individual stars in the case of *β Pegasi* and *α Herculis,* but for the other stars the mean value for the class was used. The temperatures computed from the water transmission is given in the sixth column. The seventh and eighth columns contain the temperatures computed from rad.-vis. and rad.-phot., assuming that the early type stars have a temperature of 8000°.

TABLE V.

Transmission and Intensity Ratios.

Star	Class.	% Transmission H_2O.	Rad.-Vis.	Rad.-Phot.	Temperature H_2O Trans.	Temperature Rad.-Vis.	Temperature Rad-Phot.
β Orionis	B8p	42	0.0	—0.8	4200	....	8000
α Lyræ	A	58	—0.2	—0.8	6000	8000	8000
α Aquilæ	A5	69	—0.2	—0.8	7400	8000	8000
α Aurigæ	G	48	—0.9	—2.0	4700	4700	4300
α Bootis	K	45	—1.2	—2.5	4500	4000	4000
α Tauri	K5	35	—1.9	—3.7	3700	3300	3200
γ Draconis	K5	32	—1.7	—3.7	3500	3400	3200
α Orionis	Ma	27	—2.8	—3.7	3100	2600	3200
α Scorpii	Map	27	—2.4	—3.7	3100	2900	3200
β Pegasi	Mb	29	—2.5	—4.9	3200	2800	2600
α Herculis	Mb	21	—4.0	—5.8	2700	2200	2400

The limit of error in temperature computed from water transmission is 200° or 300°, excepting in the case of *α Aquilæ.* The intensity of this star is so low and the transmission is so high that the temperature determination may be in error by + 500° or — 1000°. The value of the transmission thru water gives the temperature (Table V, column 6), by comparing this value with the line "water," Table IV, supposing the star's spectral energy curve to follow Planck's law. It may be a surprise to many astrophysicists to find *α Lyræ* and *β Orionis* at a lower temperature than *α Aquilæ.* The very low value of *β Orionis* is perhaps peculiar to that star. The class G Star, *α Aurigæ,* appears to be at a lower temperature than we should suppose from considering the Sun to be over

6000°. The highest value of the temperature which it is possible to assume for *α Aquilæ* and *α Lyræ* in view of the water transmission is 8000°; assuming this value, the temperatures of the other stars was computed by comparing the black body visibility (Table IV) with rad.-vis., Table V, column 4. This gives an impossible value for *β Orionis,* and for the other stars, values which are sometimes lower than those computed from the water transmission. If we assume *α Bootis* to be at a temperature of 4500°, the values from rad.-vis. for stars of class B and A become impossible, but stars of classes later than F would then have temperatures agreeing very well with those found from the water transmission. If, instead of using the values of rad.-vis. for the individual stars, we use the mean for the class, the temperature of *β Orionis* becomes 7500° instead of being impossible, the temperature of *α Orionis* becomes 3000° and the other stars are not appreciably affected. Comparison of the line "λ 432" of Table IV with column 5 of Table V shows that what has been said of temperature estimates from rad.-vis. is true of similar determinations from rad.-phot. In other words, the data for stars of classes G to Mb are consistent with the assumption that the spectral energy distribution follows PLANCK'S law roughly. But on this assumption the stars of classes B and A do not follow this law at all. For this reason it is impossible to invoke this law to prove that early type stars are hotter than those of later type. Again, if the blue stars follow PLANCK'S law, their temperatures must be rather low, as shown by the water transmission, and so the late classes cannot follow the law at all. I prefer to think that the stars of late type follow this law the more closely.

A comparison with the temperatures published by WILSING and SCHEINER shows good agreement for classes G and later, but these investigators assign much higher temperatures to stars of classes B and A than are compatible with the observed water transmission.

In undertaking an extended research along radiometric lines, it will be necessary to determine the atmospheric transmission curve for the ultra-violet, as well as for the visible and the infra-red. And, of course, it will be necessary to measure the atmospheric transmission, at least for some points in the spectrum, with every night's work. This will offer no great difficulty.

In his original paper, Dr. COBLENTZ expresses the hope that a sensitivity 100 times as great as that which he used may be obtained, by using a more powerful telescope, a more sensitive radiometer and more favorable mounting of the galvanometer. This would make possible radiometric work having wonderful possibilities. But even if we content ourselves with the sensitivity used by Dr. COBLENTZ at Mt. Hamilton, the future of radiometry is very bright. It is certain that, by the use of screens, our knowledge of the energy distribution in stellar spectra can be vastly increased and this knowledge correlated with laboratory experience will tell us much that is now unknown about the conditions existing in the stars. The study of double stars and variable stars will yield rich results. The question of absorption in space can be attacked with freedom from some of the difficulties which beset the observation of this phenomenon by other methods. The results which are certain to be obtained would seem to warrant some observatory possessing a large reflector in devoting two nights a week to the subject for a year or more.

SUMMARY.

The available data show no relation between the spectral energy distribution and the absolute total energy of the star.

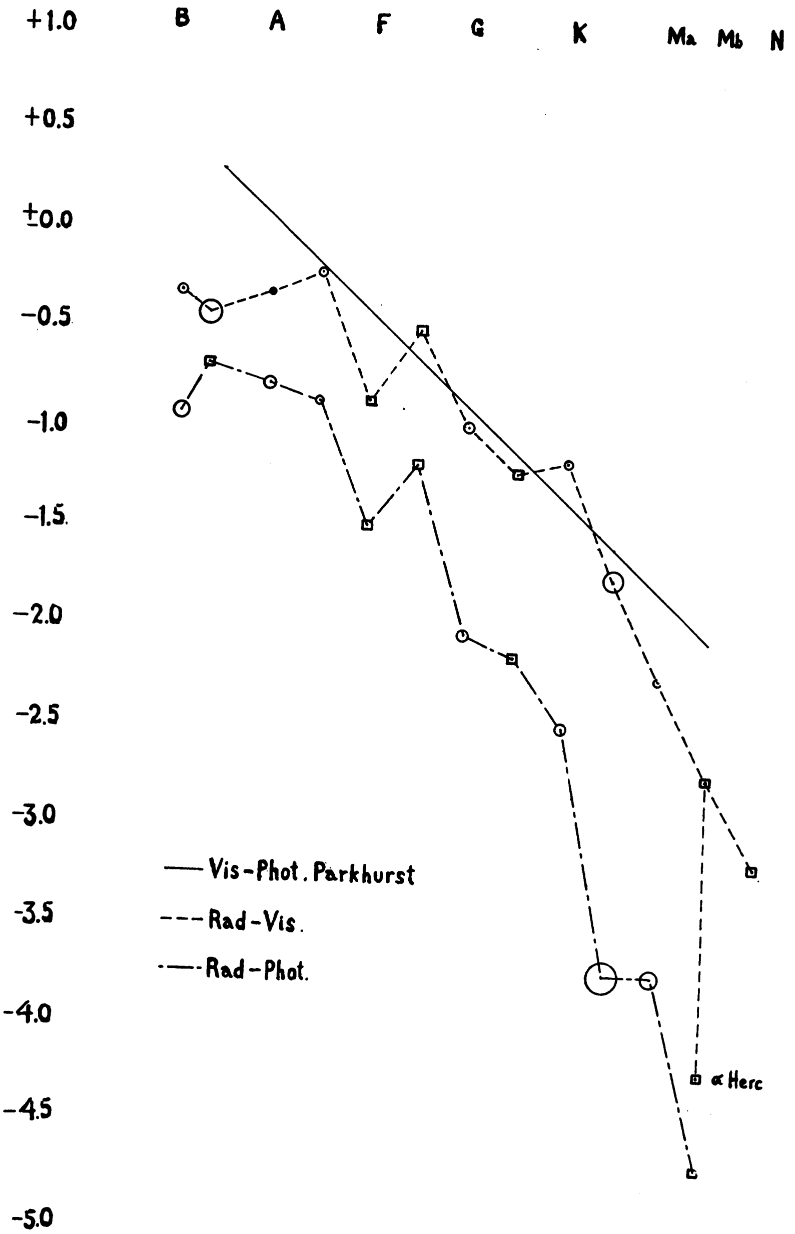
There is some evidence of absorption in space.

The fainter companion of a double star appears to have the same ratio of total energy to visibility as the primary, if any difference, the secondary is "redder."

The radiometric evidence points to a lower temperature for stars of class B than for stars of class A, but this is uncertain since the early type stars do not obey PLANCK'S law. The stars of class G to Mb seem to have spectral energy curves roughly approximating PLANCK'S law, and the temperature of such a star may be obtained from the percentage of its energy which is transmitted by a suitable screen.

The temperatures found for stars of classes G to Mb are thought to be correct within a few hundred degrees.

This paper is to quite an extent merely a more detailed statement of points brought out by Dr. COBLENTZ in his original paper.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